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SPITZER IRS OBSERVATIONS OF k+a GALAXIES: A LINK BETWEEN POLYCYCLIC AROMATIC HYDROCARBON EMISSION PROPERTIES AND ACTIVE GALACTIC NUCLEUS FEEDBACK?

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ABSTRACT

We have performed *Spitzer* InfraRed Spectrograph (IRS) low-resolution 5–12 μm spectroscopy on a sample of galaxies selected to be at three distinct poststarburst evolutionary stages based on their optical spectral indices. The resulting IRS spectra show distinctive polycyclic aromatic hydrocarbon (PAH) emission line structures at 6.2, 7.7, 8.6, and 11.3 μm and little silicate absorption, indicative of ongoing star formation. However, the PAH interline ratios, in particular the 11.3/6.2 μm and 7.7/6.2 μm ratio, show large variations. These variations are found to correlate with both time since the most recent starburst and active galactic nucleus (AGN) activity. We speculate that the evolution observed in these PAH ratios is related to an increase in AGN activity with time since starburst.

Key words: galaxies: evolution – galaxies: starburst – infrared: galaxies

1. INTRODUCTION

The nature of the connection between starbursts and active galactic nuclei (AGNs) has been long debated. While the effectiveness of AGN feedback in quenching star formation has been heralded as a key component of galaxy formation by semianalytic models (e.g., Croton et al. 2006; De Lucia & Blaizot 2007), it is only very recently that observational evidence of AGN activity coincident with poststarburst signatures has been found (Schawinski et al. 2007, 2009; Bundy et al. 2008; Kaviraj 2009). However, these discoveries form far from a consensus, with some suggestions that AGN feedback alone may not be sufficient for the truncation of star formation in these galaxies (Bundy et al. 2008; Kaviraj 2009).

The mid-IR contains unique diagnostics of the star formation, AGN activity, and dust obscuration levels of galaxies. Rest-frame 5–12 μm observations can decipher the relative strength of these attributes via investigation of the polycyclic aromatic hydrocarbon (PAH) emission properties, continuum slope, and silicate absorption strength, respectively.

Here, we utilize *Spitzer* Infrared Spectrograph (IRS) observations of a sample of galaxies which appear at different stages of poststarburst evolution as determined by their optical spectra. In particular, we use the H δ , [O II]3727 Å and 4000 Å break spectral features to identify k+a galaxies at three different epochs. k+a galaxies are typically identified via their optical spectrum, with strong absorption in the Balmer series lines, but no significant emission in the [O II]3727 Å line or other emission lines associated with star formation (Dressler & Gunn 1983; Couch & Sharples 1987; among others). This kind of optical spectrum is indicative of a galaxy which has undergone a very recent burst of star formation as the young, short-lived (<1–2 Gyr) A and B stars are still observed, but no ongoing, or very low level, star formation. Spectral modeling of k+a galaxies typically suggests a starburst in which 1%–10% of the galactic stellar mass is in the form of new stars (i.e., Balogh et al. 1999).

2. DATA

We selected 12 galaxies in three categories from the overlap between the *Spitzer* SWIRE survey and the Sloan Digital Sky Survey (SDSS) spectroscopic data set for observations with IRS. The targets were selected via their [O II]3727 Å, H δ (4101 Å),

and D4000 indices to be at distinct poststarburst stages. The H δ and D4000 indices are well established as good indicators of stellar age (i.e., Balogh et al. 1999; Kauffmann et al. 2003), while the [O II]3727 Å is a well known indicator of current star formation. Measurements of the indices were performed as per Roseboom et al. (2006). To determine our selection criteria we turn to the stellar population synthesis models of Bruzual & Charlot (2003). Models that assume an exponentially declining starburst ($\tau = 100$ Myr) on top of a passively evolving single stellar population of 11 Gyr were generated using the Bruzual & Charlot (2003) code. Burst strengths of 1%, 5% and 10% were considered. From these models we determine three sets of H δ and D4000 criteria which isolate galaxies with roughly 0.03, 0.3, and 1 Gyr of poststarburst evolution. In the case of the later two selections an additional [O II] selection cut is imposed to filter out galaxies with significant ongoing star formation. The specifics of this selection are given in Table 1.

Observations were performed with the short-low module in staring mode, two nod positions per spectral order with an offset of 20'' were observed with ramp times between 400 and 600 s. The data were reduced using a combination of the SMART (Higdon et al. 2004) and SPICE software environments. First individual ramps of the same order and nod were combined in SMART utilizing a median filtering algorithm. Sky subtraction is performed via subtraction of different order observations at the same nod position. Once combined and corrected for background/sky contributions the spectra are extracted using the SPICE pipeline assuming these objects are point sources for *Spitzer* at these wavelengths. Finally, the two nods are combined in SMART to produce the final spectrum.

Eleven of the 12 IRS spectra are found to have acceptable signal-to-noise ratio (S/N) spectra (>5); however, one of the IRS observations appears to have a featureless, flat spectrum, suggesting that the exposure times were not sufficient to detect the mid-IR features, or the IRS slit was misplaced in relation to the mid-IR emission. This failed observation is omitted in the following discussion.

3. RESULTS

Figure 1 shows the IRS spectra for the 11 sources discussed here. For comparison the starburst template of Brandl et al. (2006) is also shown. All the spectra, with the exception of

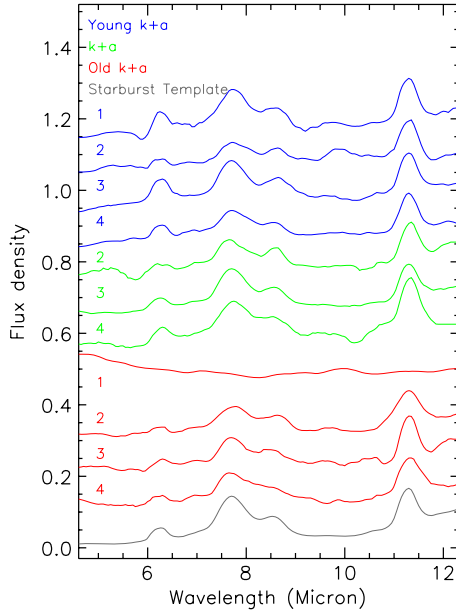


Figure 1. IRS SL spectra for the three subsamples under investigation here. For comparison the starburst template of Brandl et al. (2006) is also shown. Spectra are normalized to arbitrary flux at $11.3 \mu\text{m}$ for the sake of clarity.

Table 1
The Specifics of Target Selection Criteria

Line	Young k+a	k+a	Old k+a
O II 3727 Å (Å) ^a	...	< 6	< 6
Hδ (Å)	> 4	> 5	> 2
D4000	1–1.2	1.3–1.5	1.6–1.8
Time since burst (Myr)	25	300	1000

^a In emission.

Oka 1, show clear PAH emission features at 6.2 , 7.7 , and $11.3 \mu\text{m}$. Oka 1 is found to have a completely stellar-dominated thermal spectrum, similar to early-type galaxies observed with IRS (e.g., NGC 4552; Smith et al. 2007). Negligible silicate $9.7 \mu\text{m}$ absorption is seen in all cases.

Overall the spectra are typical of normal starburst galaxies (i.e., Brandl et al. 2006). However, one unusual feature of these spectra is the dominance of the $11.3 \mu\text{m}$ PAH feature over the $6.2 \mu\text{m}$ PAH feature in the k+a and old k+a types. To emphasize this point in Figure 2 we show the spectra stacked by type, and also the stacked and continuum-subtracted IRS spectra.

For each object key optical emission line fluxes ($\text{H}\beta$, $[\text{O III}]5007$, $\text{H}\alpha$, and $[\text{N II}]$) are determined by fitting the residual emission after the removal of best-fit stellar population models using the GANDALF IDL code (Sarzi et al. 2006).

Equivalent widths (EWs) and fluxes for the PAH features in the IRS spectra are measured via use of the IDL PAHFIT tool (Smith et al. 2007). As the mid-IR coverage is limited to $5\text{--}12 \mu\text{m}$ the determination of the continuum around $7\text{--}12 \mu\text{m}$ is troublesome due to the degeneracy between silicate absorption and PAH emission. However, as our spectra appear to have no signs of strong silicate absorption around $9.7 \mu\text{m}$ we constrain the silicate absorption to be zero by running PAHFIT with the /NO_EXTINCTION flag set.

Table 2 lists the optical properties, while Table 3 lists the mid-IR line fluxes and EWs.

To identify correlations between these observed properties and the poststarburst evolution we try to fit a two-component

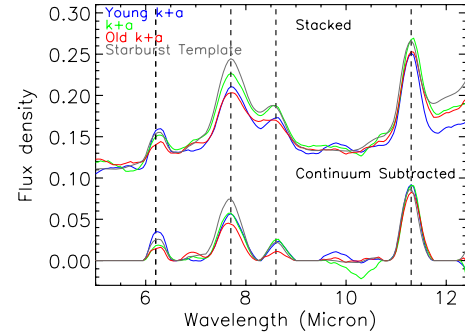


Figure 2. Stacked (top) and continuum-subtracted (bottom) IRS SL spectra for the three subsamples under investigation here. Oka 1 is omitted from the old k+a stack as it is clearly AGN dominated. For comparison the starburst template of Brandl et al. (2006) is also shown. Spectra are normalized to arbitrary flux in the $11.3 \mu\text{m}$ line for the sake of clarity.

stellar population model to each galaxy's spectrum. The models are similar to those used to select the sample; a young stellar population superimposed on a homogeneously old single stellar population. The young component is taken to be a single burst with a exponentially declining star formation rate of $\tau = 100 \text{ Myr}$. The old component is taken to be a homogeneously 11 Gyr old single stellar population. In both cases models are provided by the code of Maraston (2005). To investigate both the time since starburst and the burst fraction a total of 24 steps in burst time from 10 Myr to 5 Gyr , and 16 burst fractions from 0.01 to 0.15 are considered. The effect of dust is included according to the model of Calzetti et al. (2000) by allowing $E(B - V)$ to vary between 0 and 0.2 ($A_V \approx 0\text{--}1$). Finally, three steps in metallicity are considered; $Z = 0.5 Z_\odot$, $Z = Z_\odot$, and $Z = 2 Z_\odot$. In total 5760 models are considered. The best-fit solution is found via χ^2 fitting to the standard 25 Lick indices as well as broadband fluxes from; *Galex* NUV and FUV, *SDSS* u , g , r , i , z , and *Spitzer* $3.6 \mu\text{m}$ and $4.5 \mu\text{m}$. Where an object is undetected the upper limits are incorporated. The burst time and burst fraction are taken to be the best-fit values after marginalizing over the other model parameters. 1σ errors are taken to be region surrounding the maximum containing the 68% of the probability distribution. These quantities are quoted in Table 2.

From Table 2 it is clear that our k+a selection technique has been effective in isolating galaxies which have undergone recent starbursts. The time since burst of the young k+a sample is $\sim 0.2 \text{ Gyr}$, the k+a sample $\sim 0.6 \text{ Gyr}$, and the old k+a sample $\sim 1\text{--}3 \text{ Gyr}$. These values compare well to our predicted timescales of 0.03 , 0.3 , and 1 Gyr for the three classes. Also shown in Table 2 is the flux measured in the key AGN diagnostic lines $\text{H}\beta$, $[\text{O III}]$, $\text{H}\alpha$, and $[\text{N II}]$. By applying AGN diagnostic criteria presented in Stasińska et al. (2006), a variation on the earlier work of Baldwin et al. (1981), to these we can determine which process dominates the optical emission lines. A clear distinction can be seen between the young k+a galaxies, which are dominated by star formation, and the older classes which are either AGN-dominated, or mixtures of AGN and low-level star formation.

4. DISCUSSION

The unusual nature of the $11.3\text{--}6.2 \mu\text{m}$ PAH feature in the more evolved k+a galaxies is an interesting discovery. To quantify the nature of this Figure 3 shows the ratio of the $6.2 \mu\text{m}$ flux to the $11.3 \mu\text{m}$ and $7.7 \mu\text{m}$ lines as a function of time since starburst.

Table 2
Measured Optical Properties of Sample

ID	Name	z	Burst Time (Gyr)	Burst Strength	$H\beta^a$	[O III]5007	$H\alpha$	[N II]	Type ^b
Young k+a									
Yka1	J103254.44+581638.5	0.08	$0.27^{+0.08}_{-0.07}$	$0.3^{+0.33}_{-0.28}$	106.5	104.6	291.84	54.29	SF
Yka2	J104826.85+564026.8	0.07	$0.13^{+0.03}_{-0.03}$	$0.5^{+0.1}_{-0.3}$	141.95	146.66	450.88	92.33	SF
Yka3	J105326.83+580956.5	0.13	$0.27^{+0.08}_{-0.07}$	$0.25^{+0.25}_{-0.16}$	229.16	156.57	770.26	234.36	SF
Yka4	J163332.66+404827.0	0.08	$0.16^{+0.04}_{-0.03}$	$0.25^{+0.25}_{-0.16}$	187.53	350.97	657.17	102.81	SF
k+a									
Ka2	J104953.31+564551.3	0.182	$0.74^{+0.21}_{-0.18}$	$0.15^{+0.08}_{-0.03}$	2.56	23.98	17.16	44.74	AGN
Ka3	J110214.89+574630.6	0.14	$0.35^{+0.1}_{-0.08}$	$0.05^{+0.15}_{-0.04}$	358.86	102.05	1015.24	430.44	HYBRID
Ka4	J104319.20+563151.0	0.21	$0.58^{+0.16}_{-0.13}$	$0.08^{+0.26}_{-0.05}$	6.83	23.99	197.1	135.08	AGN
Old k+a									
Oka1	J163252.97+402056.1	0.07	$0.95^{+0.3}_{-0.2}$	$0.02^{+0.16}_{-0.04}$	19.07	22.31	15.69	30.13	AGN
Oka2	J104314.82+570941.2	0.12	$3.4^{+1.0}_{-0.7}$	$0.01^{+0.04}_{-0.01}$	22.75	15.98	87.8	48.22	HYBRID
Oka3	J104650.43+575923.9	0.18	$0.74^{+0.2}_{-0.13}$	$0.1^{+0.07}_{-0.08}$	29.5	39.05	140.06	85.88	HYBRID
Oka4	J104834.84+583311.3	0.13	$1.2^{+0.3}_{-0.3}$	$0.3^{+0.3}_{-0.28}$	158.3	49.25	519.12	249.84	HYBRID

Notes.^a Flux in units of 10^{-17} erg cm $^{-2}$ s $^{-1}$.^b As defined by Stasińska et al. (2006).

Table 3
PAH line Fluxes and Equivalent Widths

ID	Name	6.2 μm		7.7 μm		8.6 μm		11.3 μm	
		Flux ^a	EW	Flux	EW	Flux	EW	Flux	EW
Young k+a									
Yka1	J103254.44+581638.5	1.7 \pm 0.8	1.99	5.1 \pm 0.8	5.21	1.4 \pm 0.2	1.26	1.8 \pm 0.8	1.02
Yka2	J104826.85+564026.8	0.4 \pm 0.3	0.36	1.8 \pm 0.3	1.11	0.5 \pm 0.09	0.35	0.7 \pm 0.4	0.56
Yka3	J105326.83+580956.5	4.7 \pm 1.0	1.92	9.2 \pm 1.2	3.54	2.4 \pm 0.1	1.0	3.7 \pm 0.8	1.6
Yka4	J163332.66+404827.0	2.0 \pm 0.5	2.92	4.2 \pm 0.6	3.94	1.0 \pm 0.2	0.81	1.4 \pm 0.7	0.65
k+a									
Ka2	J104953.31+564551.3	0.5 \pm 0.2	0.45	2.1 \pm 0.3	1.8	0.9 \pm 0.2	0.75	1.1 \pm 0.3	0.95
Ka3	J110214.89+574630.6	3.6 \pm 0.4	1.2	11.0 \pm 1.4	3.6	2.6 \pm 0.2	0.91	4.1 \pm 0.8	1.3
Ka4	J104319.20+563151.0	1.8 \pm 0.4	0.76	5.0 \pm 0.7	2.5	1.3 \pm 0.2	0.67	3.1 \pm 0.8	1.4
old k+a									
Oka1	J163252.97+402056.1
Oka2	J104314.82+570941.2	0.8 \pm 0.3	0.28	3.6 \pm 0.3	1.7	1.0 \pm 0.08	0.59	2.7 \pm 0.5	1.8
Oka3	J104650.43+575923.9	1.1 \pm 0.2	0.24	5.2 \pm 0.8	1.5	1.0 \pm 0.2	0.32	2.2 \pm 0.6	0.89
Oka4	J104834.84+583311.3	1.1 \pm 0.3	0.30	5.3 \pm 0.9	2.1	0.9 \pm 0.2	0.37	2.8 \pm 0.5	1.2

Note.^a 10^{-21} W cm $^{-2}$.

The $S_{11.3}/S_{6.2}$ and $S_{7.7}/S_{6.2}$ PAH ratios appear to evolve from the values typical for local starbursts (Brandl et al. 2006) to higher values with increasing time since starburst. Interestingly, an equivalent rise is not seen in the $S_{11.3}/S_{7.7}$ ratio.

To quantify these trends we find the best-fit log-linear relationship between the variables. As the errors in both burst time and the flux ratios are significant simple linear regression techniques are not sufficient; hence best-fit parameters and their error are determined via a Monte Carlo simulation of the data set. In each realization the data points are “scattered” by the quoted error multiplied by a normally distributed random number. The analysis here utilizes 10,000 realizations. The mean of the slope and intercept across the realizations is then taken to be the best-fit value, while the standard deviation is the 1σ error on these properties. Performing this analysis gives the best-fit slope (intercept) for the $S_{11.3}/S_{6.2}$ ratio versus $\log_{10}(\text{burst time})$ of 1.2 ± 0.7 (2.1 ± 0.3), 1.6 ± 1.1 (4.0 ± 0.5) for the $S_{7.7}/S_{6.2}$, 0.14 ± 0.14 (0.5 ± 0.06) for the $S_{11.3}/S_{7.7}$, 0.2 ± 0.3 (1.0 ± 0.1)

for the $S_{8.6}/S_{6.2}$, and 0.94 ± 0.58 (2.2 ± 0.3) for the $S_{11.3}/S_{8.6}$. This suggests that while the observed $S_{11.3}/S_{7.7}$ is consistent with no evolution, the $S_{11.3}/S_{6.2}$, $S_{7.7}/S_{6.2}$, and $S_{11.3}/S_{8.6}$ ratios show a statistically significant nonzero evolution with burst time.

Smith et al. (2007) hypothesize that variations in PAH ratios could be generated via either weaker radiation fields, resulting in more neutral PAHs, or preferential destruction of the smallest grains in the presence of a very hard radiation field. They find that the 10 objects in their sample with the highest $S_{11.3}/S_{7.7}$ PAH ratios have clear evidence for LINER or Seyfert AGN activity at longer wavelengths, suggesting that hard radiation fields associated with AGNs could be preferentially destroying the smaller grains responsible for the 6.2 μ m and 7.7 μ m bands, leaving an excess of the larger 11.3 μ m emitting grains.

Here, we also find that all the galaxies which have high $S_{11.3}/S_{6.2}$ μ m PAH ratios have evidence of AGN activity in their optical spectra. Interestingly, we do not find that the $S_{11.3}/S_{7.7}$

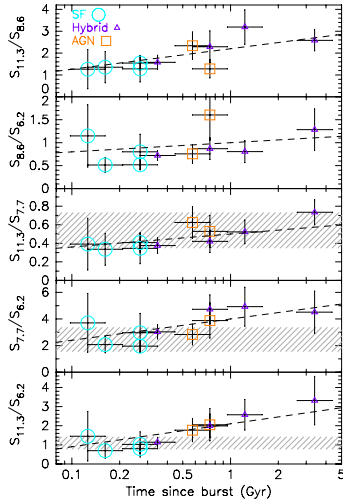


Figure 3. Flux ratios of PAH features plotted against the time since last starburst. A trend of increasing $S_{11.3}/S_{6.2}$, $S_{7.7}/S_{6.2}$, and $S_{11.3}/S_{8.6}$ with burst time can be seen. Each point is coded by its optically determined type; the circles denote SF-dominated systems, squares AGN-dominated systems, and triangles hybrid combinations of the two. The gray hatched region represents the range of ratios found for starburst galaxies from Brandl et al. (2006). The dashed line shows the best-fit linear relationship between the parameters.

PAH ratio varies with time since starburst in the same way as the $S_{11.3}/S_{6.2}$ ratio.

However, this is further complicated by the observed evolution in the $S_{11.3}/S_{8.6}$ ratio, which is what would be expected from grain destruction, but should not be possible without an accompanying $S_{11.3}/S_{7.7}$ ratio change. Even more challenging is the odd behavior of the $S_{8.6}/S_{6.2}$ ratio, which shows no evolution despite the $S_{7.7}/S_{6.2}$ showing a clear change with time since starburst. We put these irregularities down to underestimates in the error in the $8.6 \mu\text{m}$ line flux, which is heavily blended with the larger $7.7 \mu\text{m}$ feature and is thus badly effected by the poor estimates of the continuum; a serious possibility given that we only have $5\text{--}12 \mu\text{m}$ spectroscopy for these objects.

However, AGNs are only one possible explanation for this behavior of the PAH band ratios. Detailed modeling of the PAH emission models by Galliano et al. (2008) has shown that increasing the hardness of the interstellar radiation field will result in a sharp decrease in both the $S_{11.3}/S_{7.7}$ ratio and the $S_{7.7}/S_{6.2}$ ratio while destroying the smallest grains ($<10^3 \text{ \AA}$) will have the inverse affect. In addition, increasing the ionization level of the PAH-emitting grains will decrease the $S_{11.3}/S_{7.7}$ ratio while leaving the $S_{7.7}/S_{6.2}$ ratio unaffected.

Thus, the results found here can be explained via the following.

1. The ionization level is higher than normal in these objects, decreasing the $S_{11.3}/S_{7.7}$ ratio.
2. However, the ionization level is so high that the smallest grains are being destroyed, increasing both the $S_{11.3}/S_{7.7}$ and $S_{7.7}/S_{6.2}$ (and thus the $S_{11.3}/S_{6.2}$ as well).

Thus, the $S_{11.3}/S_{7.7}$ ratio may be balanced out by the competing processes and appear to have “normal” values, while the $S_{11.3}/S_{6.2}$ and $S_{7.7}/S_{6.2}$ ratios show abnormal increases. While any source which can strongly ionize and destroy the PAH emitting grains could be invoked to explain this phenomena, given the evidence of low-level AGN activity in the optical spectra for these sources we conclude that this is the most likely cause for these unusual PAH line ratios. However, this is purely

speculative and other ionization sources such as significant populations of evolved stars may be capable of levels of grain destruction and ionization seen here. The behavior of the $8.6 \mu\text{m}$ line ratios does not fit into this model, as we should see similar behavior from the $S_{8.6}/S_{6.2}$ ratio as the $S_{7.7}/S_{6.2}$, which we do not.

5. CONCLUSION

We have performed *Spitzer* IRS spectroscopy of 10 poststarburst (k+a) galaxies at three distinct evolutionary stages. In each case, the mid-IR spectra shows the signs of star-forming galaxy with no obvious AGN activity. Interestingly, we find that relative strength of the $11.3\text{--}6.2 \mu\text{m}$, $11.3\text{--}8.6 \mu\text{m}$, and $7.7\text{--}6.2 \mu\text{m}$ PAH features show some correlation with the time since last starburst, while the $11.3\text{--}7.7 \mu\text{m}$ and $S_{8.6}/S_{6.2}$ PAH ratios do not. We conclude that this behavior is most likely a result of underlying low-level AGN activity in these objects.

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SMART was developed by the IRS Team at Cornell University and is available through the Spitzer Science Center at Caltech.

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Facilities: *Spitzer* (IRS), SDSS

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